CHAPTER 10
Processing Constraints on Learning

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If research on infant cognition has taught us anything it is that very young infants are equipped with precocious abilities, ranging from their capacity to reason about physical events in the world (Baillargeon, 1987; Kellman & Spelke, 1983; Xu & Garcia, 2008), to their understanding of and ability to make inferences based on number (McCrink & Wynn, 2007; Wynn, 1992; Xu & Garcia, 2008) to their rational ability to attribute goals to agents (Bíró, Csibra, & Gergely, 2007; Gergely, Nádasdy, Csibra, & Bíró 1999) and in their understanding of intentions of others (Woodward, 2005). In the beginning of infancy work, the early onset of an ability was often associated with innately given expectations or constraints, but with increased study on what develops that changes the picture. For instance, the finding that infants can perceive the persistence of partly occluded objects at 4 months of age was initially taken as evidence for innate knowledge of principles governing objects (Kellman & Spelke, 1983). However, research since then shows that the ability to perceive the unity of occluded objects is experientially driven (Johnson, Davidow, Hall-Haro, & Frank, in press) and develops over time (e.g., Johnson & Aslin, 1995; Johnson et al., 2003). Thus, if there is a lesson to be learned, it is that the question of what develops is a complicated one. Determining the abilities with which infants come equipped, their mechanisms for obtaining and retaining knowledge, and whether and how these abilities change as a function of development is a challenging problem.

As with work on object perception, there has been a spate of recent work suggesting that infants are extremely facile learners (e.g., Gómez & Gerken, 2000; Kirkham, Slemmer, & Johnson, 2002; Safran, Aslin, & Newport, 1996a). Though the evidence is persuasive, the story is not simple. Showing that infants are fast learners is an initial step, but we need to know more about the mechanics of learning. Challenges have to do with determining how learning is constrained—how learners home in on the “right” information, whether they can do so under noisy learning conditions, and how they build on prior knowledge to generalize to more complex forms. We also need to understand how learners use memory in generalizing to cases that are similar, but not identical, to previous learning experiences.

To this end, I will discuss three types of processing constraints on learning. The first type of constraint arises from the learning process itself. The other two constraints arise from two naturally occurring memory processes: consolidation and reconsolidation. With respect to learning constraints, I will discuss research from my laboratory suggesting that learning is a dynamically guided process, arising in the interaction of internal and external pressures, and one that is fairly robust with respect to noisy input. Moreover, learners, and the structure they can acquire, change as a function of
experience. With respect to memory processes instrumental in learning, one set of findings I will describe demonstrates a type of memory consolidation occurring with sleep, one that results in generalization to novel cases. Another set of findings demonstrates how the process of memory reconsolidation enables memory change. Both memory processes are important for understanding how children sustain sensitivity to prior knowledge while incorporating new information. In contrast to “knowledge” constraints traditionally proposed in the literature on development and learning, the constraints discussed here arise naturally from the mechanics of learning and memory processes themselves.

**Constraints arising from the learning process**

Choosing among Multiple Possibilities

A particularly vexing problem has to do with how infants choose among multiple types of structure. One proposal is that learners are constrained to prefer certain kinds of information over others. Although such biases may exist, it would be a mistake to ignore other constraints on the learning process, including information in the environment itself, or the possibility that learning may arise in the interaction of the joint pressures from internal and external constraints. For instance, there is good reason to think that the ability to track dependencies between adjacent elements in sequential structure may be a default in learning (adjacent dependencies hold between elements that occur next to each other in sequence, for example, in the sentence “The boy jumped off the rock,” the words “The boy” and “boy jumped”). Many different species can track adjacent dependencies, including humans, nonhuman primates, birds, and rats (Christie & Dalrymple-Alford, 2004; Hauser, Newport, & Aslin, 2001; Terrace, Chen, & Jaswal, 1996; Terrace, Son, & Brannon, 2003; Toro & Trobá, 2005). Adjacent dependencies are learned easily by infants and by adults (Saffran et al., 1996a; Saffran, Newport, & Aslin, 1996b). They also appear to be learned incidentally when their presentation is secondary to a primary task (Saffran, Newport, Aslin, Tunick, & Barrueco, 1997). However, immediate sequential dependencies are not the only ones language learners must acquire. Many dependencies occur across longer distances, especially in language. Some examples are dependencies between auxiliaries and inflectional morphemes (e.g., is quickly running), and between nouns and verbs in number and tense agreement (The boys in the tree are laughing). If the tendency to track adjacent structure is a default, what might tune learners into more remote dependencies in sequential structure such as those separated by intervening words?

My colleagues and I have investigated this question by familiarizing infants with an artificial language that can be learned only if infants detect nonadjacent dependencies (Gómez, 2002; Gómez & Maye, 2005). Infants were exposed to one of two versions of an artificial language and were tested with sentences from each language such that a grammatical sentence for one group of infants was ungrammatical for the other group (this two-version design is used in all of the artificial language studies discussed here). Version 1 sentences followed the patterns aXb or cXd (e.g., pel-wadim-jic, vot-kicey-rud). In Version 2, the relationship between the first and third elements was reversed such that pel sentences ended with rud, and vot sentences ended with jic (aXd : pel-wadim-rud, cXb: vot-kicey-rud). In (e.g., pel-wadim-jic, vot-kicey-rud). In Figure 10.1. The a, b, c, d, and X elements were restricted to the same positions in the two languages and adjacent dependencies were identical (aX occurred in both languages as did Xd) so that sentences could only be distinguished by learning the relationships between the nonadjacent first and third words. We also manipulated the size of the pool from which the middle element was drawn (set-size = 3, 12, or 24) while holding frequency of exposure to the nonadjacent dependencies constant. The purpose of this manipulation was to determine whether high variability in the middle element would lead to better perception of nonadjacent dependencies even though these were equally frequent in all three set-size conditions. This manipulation captures a characteristic of
long-distance dependencies in natural language between frequent morphemes such as “is” and “-ing.” These frequent morphemes occur in the context of verb stems that themselves belong to very large sets (e.g., “run” in “is running,” “play” in “is playing,” “sleep” in “is sleeping”) potentially making the frequent morphemes more perceptible.

There were three possibilities for the outcome of this experiment according to three different learning models. In a statistics-driven model, learners could attend to multiple types of statistical information, weighing a type’s importance by degree of statistical regularity. By this view, learners would be biased to track conditional probabilities between adjacent elements but learning should closely mirror the statistical probabilities in the stimulus set with learners increasingly more likely to track nonadjacent dependencies as conditional probabilities between adjacent elements decrease. Thus, this model predicts a monotonically increasing function such that nonadjacent dependency learning emerges gradually with increasing set size across the $X$-axis (and decreasing conditional probabilities).

In a constraints-driven model, learners will always attend more to a favored structure even if the less favored one has greater statistical certainty. This solution assumes no learning with our stimulus materials if learners have a tendency to stick to their bias of favoring conditional probabilities (because in our language knowledge of conditional probabilities will not distinguish the two versions of the language). Thus, the learning function will be flat with discrimination at chance.

A third possibility assumes some ordering of constraints in that conditional probabilities could be a default form of learning, but also that learners will only track a preferred structure to the extent that it occurs with some minimum degree of statistical certainty. Below that point, learners will track alternative sources of information. Although adjacent dependencies may have a more privileged status than nonadjacent ones (because of perceptual salience or ease of processing), statistical structure in the input plays a determining role in whether learners will focus on one type of structure or another. This model would predict a nonlinear function such that nonadjacent dependency learning does not emerge gradually with increasing set size, but instead emerges more abruptly.

Figure 10.2 shows looking times to trained versus untrained strings after 3-min exposure to one of three variability conditions.

The results were consistent with the last proposed model, with learning occurring only under conditions of the greatest variability for infants and adults (see Gómez, 2002 and Gómez & Maye, 2005). One explanation for these findings is that learners focused on conditional probabilities between adjacent elements when these were relatively high (in the small set-size conditions), but when conditional probabilities between adjacent elements were sufficiently low (when set-size was 24) the adjacent dependencies
Generalizing with Inconsistent Input

Consistent with the question of how learners choose among multiple possibilities in input is the issue of the degree to which children can learn in the face of inconsistent input. In the course of normal language acquisition, all children are exposed to inconsistencies of one type or another, in adults’ informal speech, in children’s own ungrammatical utterances, and in the ungrammatical utterances of other learners such as playmates and siblings. Inconsistencies also occur naturally in language, for instance, in English the degree to which verbs take the regular -ed ending for the past tense, or in Spanish the extent to which feminine nouns end in -a. Other instances of inconsistencies in linguistic input are less widespread, such as when a deaf child is exposed to American Sign Language through a hearing parent who has not achieved proficiency in this language and whose repertoire of grammatical forms is not only inconsistent, but limited. In all of these instances, children must distinguish grammatical from ungrammatical instances, and they must generalize beyond the data to which they are exposed, making it relevant to ask how well infants learn on exposure to inconsistent structure. This question is also important because critics of learning have cautioned that without strong internal constraints, learners would have no way to distinguish relevant from irrelevant structure and would acquire grammar indiscriminantly, even ungrammatical forms. But is this an issue of real concern?

Gómez and Lakusta (2004) investigated this question by familiarizing 12-month-olds with an artificial language with aX and bY strings (or aY/bX strings in Language 2). There were two each of the a- and b-words and 6 each of the Xs in the middle element where what constitutes “sufficient” presumably varies as a function of the difficulty of the learning problem. In this way, the joint pressures of internal biases and external structure interact to result in dynamically guided learning. Thus, learning is constrained by the process itself without having to build in complex internal constraints for guiding the choices learners make.

Figure 10.2 Mean listening times for 18-month-olds as a function of the variability manipulation from Gómez (2002). The middle word in the sentence comes from a set of 2, 6, or 24 possible elements. Discrimination only occurs in the set-size = 24 condition.
and Ys, the latter of which were distinguishable by syllable number. Infants had to learn that a-elements went with Xs and not Ys (and vice versa for b-elements). Three groups of infants were familiarized with one of three levels of probabilistic structure (see Figure 10.3). In a 100/0-condition, all of the training strings were from the infants’ “predominant” training language. In this case, infants received strings of only the aX and bY forms. In an 83/17-condition, approximately 83% of the training strings were from the predominant aX/bY language, whereas the remaining 17% of the strings followed an aY/bX form such that one Y-word went with the two a-words as opposed the bs and an X-word went with the two bs as opposed to the as. Thus these particular strings were inconsistent with the aX/bY structure. In the 67/33-condition, the split between the predominant and nonpredominant training languages was 67% and 33%. At test, infants had to discriminate strings from the predominant language with those from the nonpredominant one, but with novel X- and Y-elements to test generalization.

We were interested in knowing whether (a) infants could separate a predominant from a nonpredominant structure such that they would show learning in the presence of inconsistent input and (b) whether learning would break down at some point as it should if the predominant structure drops below a minimum level of predictability. As seen in the looking times shown in Figure 10.4, infants in the 100/0 and 83/17 conditions showed significant levels of learning and they learned equally well as reflected in longer looking times to strings instantiated in the predominant as opposed to the nonpredominant language, suggesting that they are able to track regularities in probabilistic input even when the regularities do not occur with perfect probability (as was the case with the 83/17 ratio). Thus fairly young infants appear able to track a regular structure even with some inconsistencies present. However, learning does need to be based on some minimum degree of consistency, as demonstrated.
by the fact that infants in the 67/33-condition failed to learn.

In sum, infants appear able to separate relevant from irrelevant structure, but such learning is dependent on the quality of the signal. Thus, learning appears to be constrained as a natural by-product in infants’ processing of statistical structure.

**Bootstrapping from Simpler to More Difficult Structure**

A third way that learning is constrained by the learning process stems from prior learning. In the real world, and particularly during early development, learning is unlikely to result in an end state. Instead, learners encounter new examples with potential to build on, interfere with, or alter the type of generalizations they are able to make. Furthermore, the types of generalizations infants make are influenced by their prior experience. As such, it is important to begin to understand how prior knowledge supports or detracts from the learning of new or more complex forms.

There is precedent for the role of prior experience already in language acquisition in the work on infant speech perception showing that infants can discriminate speech sounds that occur in other languages early on in development but become more limited in the nonnative forms they can discriminate as they become more attuned to their native language input (Best, McRoberts, & Sithole, 1988; Polka & Werker, 1994; Werker & Tees, 1984). Presumably this change is a function of experience. Similar findings have been reported in the infant learning literature. Gerken and Boltt (in press) find that younger 7-month-olds are able to acquire an unnatural linguistic rule that older 9-month-olds cannot. Presumably increased tuning to the statistics of English helps older infants ignore unnatural generalizations in favor of linguistically natural ones. In this way, experience constrains the types of generalizations infants will make, but can prior experience also enable learning of forms that are normally too difficult to acquire?

Evidence for this comes from studies investigating how prior learning might bootstrap sensitivity to complex syntactic patterns, and specifically how prior learning impacts the acquisition of nonadjacent dependencies (Lany & Gómez, 2008). Infants in these studies were 12-month-olds who in previous studies have been unable to track nonadjacent structure (Gómez & Maye, 2005). Infants were familiarized with aX and bY strings, where X- and Y-elements were distinguishable by syllable number, and where infants had to learn that a-elements went with Xs and not Ys (and vice versa for b-elements). After familiarization with the aX/bY structure infants were able to detect the aX and bY relationships in a more complex language involving long-distance dependencies (e.g., in acX and bcY sentences). See the results in Figure 10.5. This language was particularly challenging for this age group because the intervening e-element required the infants to track nonadjacent dependencies between a- and X- and b- and Y-words. A control group who did not receive prior experience with the simpler “adjacent” form of the language was not able to track the critical dependencies when they were nonadjacent. Thus, with prior exposure to simpler adjacent structure infants are able to detect the more difficult nonadjacent form. This finding is relevant for showing how infants might scaffold learning of more difficult structure from learning of more simple forms and for showing how prior experience can affect later learning. These findings also demonstrate how constraints can arise from the learning process itself, as opposed to being part of learners’ knowledge beforehand.

In summary, the findings showing that (1) internal biases and external statistics interact to guide the choice of which structure is learned when multiple possibilities are available, (2) learning of a predominant form can persist in the face of inconsistent input but only to a point, and (3) prior experience can in some cases constrain and in others enable learning, are important for increasing our understanding of how learners negotiate complex statistical structure. They also shed light on how constraints and statistical structure both contribute to this process. Particularly important are the insights they provide into how the learning process.
across wake states, sleep is particularly instrumental in memory consolidation. Additionally, memories are updated with new information as a matter of course in learning. A candidate process for such updating is memory reconsolidation. Mounting evidence suggests that when memories are reactivated, they become labile and open to change. Retrieval can reinforce the reactivated memory, or update it through the incorporation of new information. Such transformed memories then undergo a time-dependent reconsolidation process. Although the idea that memories are malleable is not new in cognitive development (e.g., Loftus, 2005), the mechanism underlying such change has not been well understood. Work on memory reconsolidation has begun to define the critical determinants of episodic memory change and holds promise for identifying the conditions affecting the updating of prior knowledge in learning and cognitive development. Thus, memory consolidation and reconsolidation both have implications for constraining children’s generalizations. These topics are addressed below.

**Memory Consolidation**

Memory consolidation is a process in which a newly formed memory trace is converted to a stable, less disruptable state over a period of days to years (McGaugh, 2000). In addition to stabilizing the memory, consolidation is thought to result in an enhancement of the remembered information in the form of greater accuracy and speed of execution, and better generalization. Memories are also thought to become more integrated with existing knowledge as a function of consolidation. Although there is evidence that memories become stabilized during wake states (Brashers-Krug, Shadmehr, & Bizzi, 1996, Mullbacher et al., 2002, Walker, Brakefield, Hobson, & Stickgold, 2003), memory enhancement appears to be a unique product of sleep (Fischer, Hallschmid, Elsner, & Born, 2002; Gais, Plihal, Wagner, & Born, 2000; Karni, Tanne, Rubenstein, Askenasy, & Sag, 1994; Korman, Raz, Flash, & Karni, 2003; Stickgold, James, & Hobson, 2002a; Stickgold, Whidbee, Schirmer, Patel, & Hobson, 2002b; Walker et al. 2002a; Walker,
Brakefield, Hobson, & Stickgold, 2002b; Walker & Stickgold, 2006). Importantly, these improvements appear to arise from molecular, cellular, and systems-level processes that are specifically linked with sleep. For instance, there is some evidence that patterns of activation occurring during training reappear during rapid eye movement (REM) sleep (e.g., Maquet et al., 2000; Wilson & McNaughton, 1994; Euston, Tatsuno, & McNaughton, 2007) and immediate performance on a learning task can be shown to correlate with the magnitude of later brain activity during REM (Peigneux et al., 2003). While these findings suggest that brain activity during sleep is affected by training earlier in the day, brain activity during sleep also correlates with later memory performance and improvement, demonstrating a link not just between the original learning experience and sleep but also between sleep and memory consolidation as measured after sleep (Peigneux et al., 2004). The findings linking brain activity to earlier training, and brain activity to later consolidation, are important for ruling out explanations of memory stabilization and enhancement having to do with a decrease in sensory input (or a decrease in interference) during sleep.

How does sleep affect the consolidation of new learning? Research with adults shows that learners were faster and more accurate in tapping out a sequence with their fingers in a procedural learning task after sleep than before (Walker et al., 2003). Sleep also appears to be implicated in a type of memory consolidation that leads to generalization. Fenn, Nusbaum, and Margoliash (2003) found that adults were better able to recognize phonemes in new words after a night of sleep than after an equivalent interval of wake–time during the day. Learners were tested 12 h after training and either slept or not during this interval. Participants who did not sleep showed decreased levels of recognition whereas those who did sleep showed the same high levels of generalization on novel words as learners tested immediately after training. The time of day learning took place was not a factor. Groups who learned in the morning and in the evening had identical performance gains on novel words after a 24-h interval (during which both groups slept).

In addition to better performance and generalization, sleep has also been implicated in qualitative changes in memory having to do with gaining insight into a problem solution (Wagner, Gais, Haider, Verleger, & Born, 2004). Participants exposed to a problem that could be solved either in an iterative step-by-step fashion or according to a hidden rule were more likely to make the critical insight regarding the hidden rule after sleep than after an equivalent time awake. Two times as many of the participants in the sleep group detected the hidden rule as compared to the group who did not sleep, suggesting that sleep was implicated in a transformation in memory that made it easier for learners to discover the hidden rule. Sleep has also been implicated in memory transformations involving transitive inference of relations (Ellenbogen, Hu, Payne, Titone, & Walker, 2007), and learning of higher-order associations and their generalization (Cohen, Pascual-Leone, Press, & Robertson, 2005; Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003; Spencer, Sunm, & Ivry, 2006). Ellenbogen et al. trained participants on visual stimuli of the form A>B (A precedes B), B>C, C>D, D>E, E>F then tested them for generalization to novel inference pairs (B>D, C>E, and B>E) after varying intervals that either did or did not contain sleep (20 min, 12 h wake, 12 h sleep, 24 h). Retention of the learned pairs was similarly high for all groups (85%), but generalization occurred only for groups tested 12 or more hours later, with sleep in the 12-h groups providing an additional boost for the most distant, and most difficult, inference pair (B>E, 69% wake, 93% sleep). Additionally, Cohen et al. (2005) found that transfer of goal-based versus movement-based skill in a serial reaction-time task improved differentially during wake and sleep with knowledge of movements themselves improving during wake and knowledge involving goals improving with sleep.

Although there is an established literature on patterns of infant sleep–wake states (Kleitman & Engelmann, 1953; Thoman, 1990), little is known about the role of sleep in infant learning with the exception that sleep–wake
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state organization is a predictor of cognitive development in infancy (Gertner et al., 2002), as well as the finding that sleep plays an instrumental role in brain development in animals (Frank, Issa, Stryker, & Keck, 2001). However, given the adult findings on the importance of sleep in memory consolidation, there is every reason to think that sleep is also implicated in infant memory. Indeed, recent research supports this view (Gómez, Bootzin, & Nadel, 2006).

In the first experiment designed to test the effects of sleep on learning, 15-month-old infants were exposed to a learning experience prior to a nap then were tested afterward. The infants were familiarized with the artificial language discussed in the first section on learning constraints detailed above. The artificial language required infants to track sequential dependencies between the first and third words in sentences such as pel-wadim-jic or vot-kicey-rud. Recall that previous research from our laboratory showed that the nonadjacent relationships between the first and third words are learned only when there is high variability in the middle position (created by selecting middle words from a large as opposed to a small set), making the flanking nonadjacent word-dependencies more salient perceptually (Gómez, 2002; Gómez & Maye, 2005). Because the two versions of the language were identical with respect to absolute position of words and dependencies between adjacent words, they can only be distinguished by noting the nonadjacent relationship between the first and third words. This feature of the language enabled us to ask whether sleep-enhanced memory of specific nonadjacent word-pairs (e.g. that pel predicted jic), or promoted learning of an abstract rule (that the first word predicts the last in an utterance, despite the specific words involved).

Infants were familiarized with the language in their homes by a research assistant who played the artificial language from a tape recorder while playing quietly with the infant. Familiarization lasted approximately 15 min. Infants were tested in the laboratory 4 h after familiarization. There were two groups of primary interest: infants who napped between familiarization and test and those who did not nap. Typically, infants this age look longer to familiar versus unfamiliar strings immediately after familiarization, reflecting memory of specific nonadjacent word-pairs (Gómez & Maye, 2005). However, if sleep induces a transformation in memory, infants might remember something more abstract involving a predictive relationship between the first and third words. If so, infants might show a preference for the nonadjacent word-pairs encountered on the first trial of the test even when they were not the exact nonadjacent words encountered earlier. If time alone plays a role in memory consolidation, infants in both the nap and no-nap groups should show the same pattern of effects. However, if sleep is the determining factor, then performance should differ between the two conditions. A nap-control group was also tested to determine whether sleep alone would alter learning. This group was exposed to the artificial language but the middle word came from a set of only three items, a condition that does not normally lead to nonadjacent dependency learning.

Infants were tested on sentences that both preserved the specific nonadjacent dependency encountered during familiarization and on sentences that contained violations of the specific nonadjacent dependency. The head-turn preference method was used to assess discrimination of the two stimulus types in the form of listening time differences (Kemler Nelson et al., 1995). The results are shown in Figure 10.6.

Infants in the no-nap group listened longer to familiar over unfamiliar trials consistent with veridical memory of specific nonadjacent word-pairs. In contrast, infants in the nap group listened longer to sentences consistent with the trial-type encountered on the first test trial, suggesting they had abstracted away from specific nonadjacent words such that they noticed particular nonadjacent dependencies on the first test trial (whether identical or not) and showed a greater tendency to listen to strings with the same nonadjacent dependencies in remaining trials. The control group showed no learning whatsoever, eliminating the possibility that sleep alone can alter memory apart from the learning manipulation.
More recently, we have asked whether 15-month-olds need to nap fairly soon after learning or whether, like adults, any sleep later in the day will do (Hupbach, Gómez, Bootzin, & Nadel, in press). We familiarized two groups of infants with the artificial language used in Gómez (2002) and Gómez et al. (2006). One group was scheduled at a time of day when they were likely to nap in the 4-h interval after familiarization. Another group was scheduled when they were not likely to nap until at least 4 h later. Both groups were tested 24 h after familiarization. Thus, all infants slept during the night, but only the nap-group slept in the 4-h interval after familiarization. Interestingly, the nap group showed generalization 24 h later, whereas the no-nap group showed no learning of any kind. Thus, sleep fairly soon after a learning experience appears to be critical not only for memory retention, but for abstraction of the learned information.

These findings raise important questions about the role of sleep in memory change. For one, how do memories become more abstract? One possibility is that infants are sensitive to both specific and abstract information but weight these differentially before and after sleep. A second is that infants forget specific details of the stimulus with sleep. Although infants may indeed weight specific and abstract information differently immediately after learning, the idea that infants forget specific details of the stimulus with sleep seems more likely given that infants who did not sleep immediately after test showed no memory of the artificial language 24 h later.

Additionally, what kind of sleep is involved? Plihal and Born (1997) found that declarative learning in a paired-associates task was enhanced during slow-wave sleep (SWS) and procedural learning in a mirror-tracing task was linked with REM. It is not clear whether our artificial language studies engage declarative or procedural knowledge, however the naps of children this age contain components of both REM and SWS (Louis, Cannard, Bastuji, & Challamel, 1997). Thus, with testing of sleep architecture, it should be possible to determine which specific stage or stages of sleep are most involved.

Finally, the findings showing that sleep soon after learning is important for retention raises the question of when in childhood learning becomes less nap-dependent such that children, like adults (Gais et al., 2007), are able to consolidate memories with only nighttime sleep. It is tempting to assume that the rate at which children nap is sufficient and necessary for any given age, but differences in cultural practice and in individual families’ schedules make it difficult to use existing napping norms to answer this question.
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In sum, these findings suggest that the memory process itself is instrumental in constraining learning. In our particular studies, memory consolidation associated with sleep introduced flexibility into performance such that infants abstracted a pattern and detected it at test regardless of whether it was instantiated exactly as before. In this way, the process of memory consolidation gives rise to plasticity in learning by sustaining sensitivity to previously encountered information, while enabling children to generalize to similar but not identical cases. Memory change involving abstraction may be particularly important for developing infants who must retain key aspects of prior experience while generalizing in novel situations.

I turn next to the role of memory reconsolidation in learning, starting with a discussion of how the processes of memory consolidation and reconsolidation differ.

Memory Reconsolidation

Memory consolidation is a process that stabilizes a new memory trace. There are changes in the brain structures critical for memory storage and/or retrieval at both cellular and systems levels. At the cellular level, there are changes in synaptic efficacy and at the systems level, there are thought to be changes in memory expression such that it is no longer dependent on the hippocampus (Squire, Cohen, & Nadel, 1984). Two tenets of this process are that once complete, memories are stable and no longer subject to change. Additionally, consolidation is thought to involve strengthening of the memory as opposed to memory modification. How then does new information get incorporated? The answer lies in a phenomenon known as memory reconsolidation. Contrary to the view that memories become stable and resistant to change, reactivating a memory appears to make it labile and open to change. By this view, reactivation transfers memory from a passive to an active state during which it can be altered and/or disrupted (Lewis, 1979; Misanin, Miller, & Lewis, 1968; Nader, Schafe, & Le Doux, 2000; see also Sara, 2000). Altered memories must then undergo a time-dependent period of reconsolidation to register change.

Nader et al. (2000) showed that reactivation of a fear-response could bring a well-consolidated fear memory back to a labile state that could then be disrupted by inhibiting protein synthesis in the amygdala (the same treatment that disrupts initial consolidation), demonstrating that memories require de novo protein synthesis in order to survive. Importantly, impairment was not observed in the absence of reactivation. Reconsolidation has since been demonstrated in variety of species and learning situations and it appears to be distinct from consolidation in its neurobiological process (for a review, see Dudai, 2006).

Reconsolidation has also been recently demonstrated in two procedural memory tasks with humans. Walker et al. (2003) trained adult participants to tap out a visually presented sequence (e.g., 4-1-3-2-4) on a numeric keypad with their corresponding fingers. Twenty-four hours later, participants learned a second sequence (e.g., 2-3-1-4-2) in one of two conditions (one in which the first sequence was either briefly rehearsed, reactivating it, or one in which it was not rehearsed). Participants were then tested 24 h later for their accuracy and speed on the original sequence. Performance in the group that was reminded was significantly impaired in comparison to the group who did not rehearse the first sequence before learning the second one, demonstrating that reactivating a memory destabilizes it such that a competing motor pattern can then interfere. There is also evidence from a procedural learning task with 3-month-olds that reconsolidation occurs in very young infants. Galluccio (2005) and Galluccio and Rowee-Collier (2005) investigated the effects of reactivated memories on infants trained to kick their foot to activate a mobile. After a delay, the moving mobile was presented for a brief period during which it was no longer attached to the baby’s foot (reminding the child of the original learning experience). After reactivation, infants were exposed a novel mobile. One day later, infants who were exposed to the novel mobile no longer recognized the original one—they responded solely with a kicking response to the novel mobile, suggesting that the experience with the new mobile had overwritten memory for the old one.
These findings were important for demonstrating how memories could be altered by new information, and thus are relevant to theories of learning and development, such as those having to do with the misinformation effect (Loftus, 2005). However, they also raised important questions. First, how broadly does reconsolidation apply to different forms of memory? The reconsolidation effects described thus far apply to tasks involving implicit memory, a form of memory that does not require conscious recollection. But does reconsolidation also apply to explicit memory, a form of memory that allows for the conscious recollection of events (episodic memory) and facts (semantic memory)? Additionally, previous demonstrations of reconsolidation have shown that new information interferes with previous learning, but can reconsolidation also be instrumental when learners have to incorporate new information into established memories?

These questions have been explored in the context of an explicit memory paradigm developed by Hupbach, Gómez, Hardt, and Nadel (2007). Adult participants learned a set of 20 common objects during a first session (e.g., bandaid, sunglasses, pencil, cup, sponge, etc.). The objects were contained in a yellow basket and were pulled out one-by-one and named. The participants were asked to recall the items immediately after exposure to the entire set. The procedure was then repeated until participants recalled at least 17 of the 20 objects or completed four rounds of recall trials. Forty-eight hours later, participants were reminded of the original learning experience or not. Reminding took the form of the same experimenter taking the participant back to the same location in the psychology building and asking them if they remembered what they had done previously with the yellow basket. Participants were encouraged to describe the procedure only. They were stopped if they began to recall any of the objects. Participants in the no-reminder group were taken by a different experimenter to a different location in the building and were not reminded of the yellow basket. All participants learned a second set of objects (in the case of the reminder group learning occurred immediately after reminding). Forty-eight hours later in a third session, participants were asked to recall the first set of objects only, the objects learned in the original session.

Reminded subjects showed a high number of intrusions from the second set of objects when recalling the first set, whereas participants who had not been reminded showed virtually no intrusions, demonstrating that the updating of preexisting memory is dependent on reactivation of that memory (Panel 1 in Figure 10.7). Importantly, the effect is not evident immediately after learning the second set of objects as would have been predicted if this were retroactive interference (Panel 2). Instead the effect took time to emerge. Therefore, as with animal fear conditioning (e.g., Nader et al., 2000) and human procedural memory (Walker et al., 2003), reactivated episodic memories appear to undergo a time-dependent reconsolidation process. However, our findings differ in an important way from previous ones in demonstrating constructive memory effects as opposed to interference of new information on old memories. Furthermore, the updating effect occurs only for the reactivated memory. When participants were asked to recall objects from the second training session, intrusions of objects from the original memory were rare, arguing against simple source-memory confusion (Panel 3).

Although conducted with adults, this memory-reconsolidation process is relevant for understanding memory updating generally in learning and development. Such a process appears to depend on reactivating memory through some form of reminding, providing new information at the time of reactivation, and allowing time for the new information to be incorporated with the old.

We have also tested 5- and 9-year-old children to see whether the updating effect occurs at earlier points in developmental time (Hupbach, Gómez, & Nadel, in preparation). It would be particularly informative to know whether 5-year-olds show the asymmetrical updating effect in the form of updating of the original memory because source memory errors are high in this age group relative to children 6 years of age and older (Drummey & Newcomb, 2002). Five-year-olds might be just as likely to intrude objects from the first learning
experience into their recall of the second set as they are to include the second set of objects into the original memory. Children were tested with a similar design as the adults with three exceptions: 9-year-olds were tested with 12 objects and 5-year-olds with 8, the children were tested in their homes instead of in the laboratory, and the delays between sessions were 24 h instead of 48 h in duration.

Children of both ages showed robust intrusion effects. Importantly, 5-year-olds showed the asymmetrical updating effect. Although children this age tend to have difficulty monitoring the source of newly acquired information, they do not show such errors when a prior memory is reactivated at a later point in time. As with the adults, the effect is time-dependent. It does not appear when children are asked to recall the original list immediately after learning the second one. Instead, the effect only shows up 24 h later after memory reconsolidation has taken place.

One question has to do with the cues that trigger memory reconsolidation and updating. For adults and 5-year-old children, unfamiliar locations in themselves can serve as a reminder (updating occurs even when the experimenter is different and the reminder question is not asked, as long as the spatial context remains the same, Hupbach, Hardt, Gómez, & Nadel, 2008; Hupbach, Gómez, & Nadel, in preparation). However, not surprisingly, spatial context does not serve as a reminder when children are tested in a familiar spatial context such as when they are tested in their homes. In that case, the experimenter and reminder question together serve to reactivate memory (Hupbach, Gómez, & Nadel, in preparation). The importance of spatial context for determining whether memories of events are reactivated and updated makes sense given that the particulars of a current situation often determine which responses are appropriate (see Nadel, 2007). Other cues, may act as reminders for a different reason. Having an unknown person visit and interact with a child at home is an unusual and salient event, whereas an interaction with a new person is not so unusual when a child is in an unfamiliar location, as the data with children show. In that case, spatial location serves as the reminder

![Figure 10.7 Mean number of objects correctly and falsely recalled in the reminder and the no-reminder groups. Panel 1: Recall of Set 1 in Session 3. Panel 2: Immediate recall of Set 1 in Session 2. Panel 3: Recall of Set 2 in Session 3. Error bars represent standard errors of means. Note in Panels 2 and 3 that there are no intrusions in the reminder conditions. From Hupbach, Gómez, Hardt, and Nadel (2007).](image-url)
Regardless of which reminders reactivate memory and why, the triggers demonstrated thus far are incidental in nature. They occur frequently in experience with potential to reactivate memories continually, resulting in a process of learning and memory that is fluid, as opposed to static, in nature, that may play a central role in cognitive development.

**SUMMARY**

The central problem in cognitive development is understanding how cognition grows and changes over time. Research has had tended to focus on changes in the knowledge base itself in terms of documenting types of knowledge and abilities children exhibit at different ages, and asking how that knowledge constrains the choices children make. An example is children’s tendency to extend labels to novel objects taxonomically, within the same category, as opposed to extending them to thematically related choices (e.g., extending a novel label for dog to a pig, but not to a bone; see Markman & Hutchison, 1984). Although children may well employ such constraints, it is important to ask whether and how they are learned. One possibility is that children note the consistency of the association between a label and objects of similar shape (e.g., cups come in a variety of colors and sizes, but they are similar in their shape), allowing them to generalize the principle that categories contain objects of similar shapes. This principle is consistent with children’s taxonomic choices and is relevant for understanding how such choices come to be manifested in children’s behavior (Colunga & Smith, 2004, 2005; Jones & Smith, 2002; Smith, Jones, Landau, Gershkoff-Stowe, & Samuelson, 2002). In this way, experience itself can lead to the formation of a general principle (see Lany & Gómez, in press, for a more thorough discussion of this idea).

In the tradition of emphasizing developmental processes, an aspect of development explored here is how learning and memory processes themselves might serve to constrain learning. There are processes that appear to guide learning dynamically, enabling infants to switch from learning of a simpler form of information (e.g., adjacent dependencies) when that source is not informative to other forms of structure that are not as simple (e.g., nonadjacent dependencies; Gómez, 2002). In this way, the choice of which structure to learn can arise naturally from the competing pressures of internal biases and information in the environment. We have also documented learning under noisy conditions showing that infant learners can track a predominant probabilistic structure despite irregularities in the input, and can even generalize on this basis (Gómez & Lakusta, 2004). Importantly learning diminishes, as it should, when the input contains higher levels of irregular structure, demonstrating that learning is constrained by the reliability of the information children encounter. Finally, we have seen how the information children acquire at one point in time can constrain what they are able to learn at older ages (Gerken & Bollt, in press) and can also enable learning of more difficult forms (Lany & Gómez, 2008). This work raises questions regarding the types of processing biases available to learners and which biases are likely to be employed in different learning situations. The findings also raise questions about the way learning changes as infants’ cognitive processes are increasingly able to handle more difficult information. Do the learning processes themselves become more complex or are they able to execute over more difficult information?

We have also documented the role of memory processes in constraining learning, both the role of memory consolidation and sleep in transforming learned experiences into a more abstract form (Gómez et al., 2006) and the role of reconsolidation in constructive memory (Hupbach, Gómez, Hardt, & Nadel, 2007). Both memory processes are important for understanding how children sustain sensitivity to prior knowledge while incorporating new information. In addition to the role of memory processes in constraining learning, it is important to test memory to ensure that the behavioral effects seen immediately after a learning phase are not simply the result of short-term acclimatization to a stimulus as opposed to a more permanent change. That is, for the learning we
observe in the laboratory to contribute in any meaningful way to development, it should result in some kind of memory change that is retained long enough to be reinforced or to be instrumental in later learning. Additionally, what is remembered after sleep or after a 24-h delay (Gómez et al., 2006; Hupbach et al., in press) may be very different than what is remembered immediately after learning. Importantly, adult work shows distinct processes of stabilization and enhancement in memory consolidation. As such, it will be important to fill in the developmental picture of how infant memories stabilize over wake and sleep states, whether this differs at different ages, and how this is linked to what we already know about infant memory.

With respect to the role of reconsolidation in memory change, additional research will be necessary for characterizing reconsolidation more fully, in terms of determining whether the effect is transient or long-lasting, whether the process is similar for older as compared to younger memories, how it is affected by sleep, and how it is affected by different kinds of reminders (e.g., what happens when learners are asked to recall an established memory as opposed to reactivating it implicitly?). Most importantly, how do these factors change across development and as children gain expertise in a particular domain, such as in language? The answers to these questions will be important for understanding the scope and limits of reconsolidation—and the implications for learning and development are far-reaching. In particular, the interference effects documented in the animal literature (Nader et al., 2000) and in human procedural memory (Walker et al., 2003) may explain how children recover from incorrect, or erroneous, generalizations. Presumably, if a generalization is activated, though incorrect, it will be overwritten in time by more statistically probable data. Furthermore, the memory updating effects that occur with reconsolidation of episodic memories are relevant to understanding how learners incorporate new information or experiences into prior memory. An important consideration is the fact that reconsolidation of episodic memory should be hippocampally mediated, but the hippocampus is not fully developed in humans until approximately 18–24 months (Nadel & Hupbach, 2008). Thus, reconsolidation involving episodic memory should not occur much before 18–24 months of age, but it should occur later. Further research will be necessary for understanding the exact nature of reactivation and reconsolidation of memories at younger ages, such as in the findings reported by Galluccio and Rovee-Collier (2005).

In sum, in contrast to “knowledge” constraints traditionally proposed in the literature on development and learning, the constraints proposed and discussed here arise naturally from the mechanics of learning and memory processes themselves.

**References**


Colunga, E., & Smith, L. B. (2005). From the lexicon to expectations about kinds: A role for
Hupbach, A., Gómez, R. L., & Nadel, L. Memory capacity increases between 5- and 9-years of age, but memory reconsolidation is present at both ages. Manuscript in preparation.
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sleep of overnight improvement of a perceptual skill. *Science* 265, 679–82.


AQ1: Please consider the edit done to the sentence "In the beginning of infancy work..." in the part "what develops..."

AQ2: Please update Gerken and Bollt, in press.

AQ3: Please update Johnson et al. in press.

AQ4: Lany et al. 2007 is not cited in the text.

AQ5: Please provide the names of first six authors in Maquet et al. 2000.